

DEPENDENCE OF LONG BONE FLEXURAL PROPERTIES ON BONE MINERAL DISTRIBUTION

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INTRODUCTION

The objective of this study is to assess whether a non-invasive determination of long bone cross-sectional areal properties using bone densitometry accurately estimates true long bone flexural properties. In this study, section properties of two pairs of human female embalmed tibiae were compared using two methods: (1) special analysis of bone densitometry data, and (2) experimental determination of flexural rigidities from bone surface strain measurements during controlled loading.

METHODS

Principal Area Moments of Inertia and Major Axis Orientation from Bone Densitometry

The proximal end of each tibia was potted with bone cement and inserted into a precision indexer. Using an inclinometer ($\pm 0.1^\circ$), the tibia was oriented with the medial-lateral plane normal to gravity. This was the reference orientation for both densitometry and strain measurements. The tibia long axis was perpendicular to the scan plane and all scans started at the same point. Three non-coplanar scans were taken of the entire tibia with an Hologic QDR-1000/W densitometer at rotations of 0° , 45° , and 90° about the tibia long axis.

Pixel attenuation data from the high energy beam were first converted to equivalent aluminum thicknesses using an aluminum calibration wedge. The equivalent aluminum thicknesses were then used to compute area moments (zeroeth, first, and second) line by line for each of the scans by integrating across

the scan width (Martin and Burr, 1984). The principal area moments of inertia (second moments) and orientation of the principal major axis at each scan line, or bone cross-section, were determined by diagonalizing the moment matrix obtained from the three independent scans (Cleek and Whalen, 1993).

Principal Flexural Rigidities and Major Axis Orientation from Strain Measurements

After scanning, four single element strain gages, aligned along the long axis of the tibia, were bonded uniformly around the circumference at each of four cross-sections. Beginning with the tibia in the reference orientation, a known load producing a known bending moment at each cross-section was applied at the distal end of the tibia. Strain data were recorded from all strain gages as the indexer was rotated through 360° in 45° degree increments.

To compute flexural rigidities (defined as $EI^*_x = \int E(x,y)y^2 dA$, $EI^*_y = \int E(x,y)x^2 dA$) from strain gage data, the curvatures were first computed, the section centroid was then calculated from curvatures and strains, and finally, the section flexural rigidities about the centroid were derived from simultaneous solution of equations using the known curvatures and known bending moments (Gies and Carter, 1982).

RESULTS

Principal Angle

The orientation of the principal major axes of the bone mineral computed non-invasively by

densitometry correlated with those computed from surface strain measurements (fig. 1). For pair 1, the mean difference in angle between the two measurement methods was -0.92 ± 1.34 degrees and -2.19 ± 4.89 degrees for the left and right tibiae, respectively. Similarly, the mean difference in angle for the second pair of tibiae was -2.39 ± 2.22 degrees and 5.17 ± 2.00 degrees for the left and right tibiae, respectively. The mean angle difference for the pooled data was -0.08 ± 4.13 degrees.

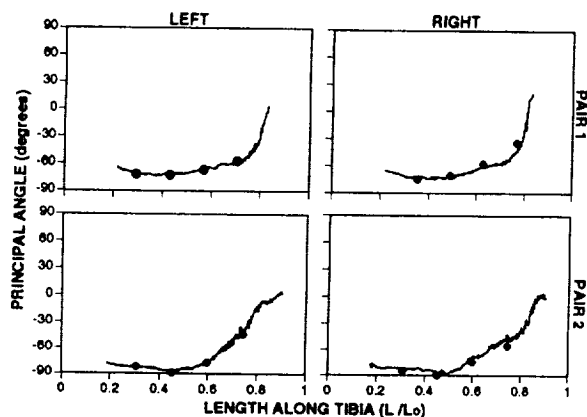


Figure 1. Principal angle of the major axis. Coordinate frame (viewed from distal end): 0-medial; 90-anterior, -90-posterior. Fractional length presented from proximal to distal end. Continuous trace of principal angle from densitometry and individual data points from surface strain measurements. Principal angle data for pair 2 have been shifted +12 degrees with respect to the medial-lateral plane for the purpose of visualization.

Principal Moments of Inertia

The principal area moments of inertia of bone mineral calculated from densitometry analysis were linearly related ($r=.95$ for pair 1, $r=.94$ for pair 2) to the principal flexural rigidities computed from analysis of strain gage data.

Effective Flexural Modulus

An "effective" elastic modulus (E_{eff}) was computed about each principal flexural plane as the experimental flexural rigidity (EI_{min} and EI_{max}) normalized by the moment of inertia (I_{min} and I_{max}) of the bone mineral, as calculated from densitometry. When computed at each cross-section, the mean value of E_{eff} was 20.1 ± 2.39 GPa and 16.3 ± 2.39 GPa for pair 1 and pair 2, respectively, while the regression for pooled data from both pairs yielded an E_{eff} of 18.25 GPa ($r=.95$) (fig. 2).

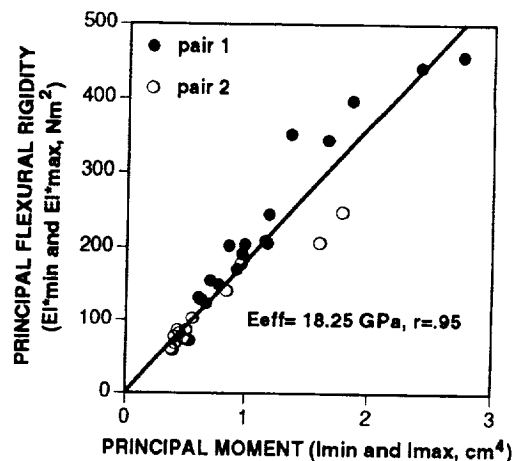


Figure 2. Principal flexural rigidities from strain data vs. moments of inertia from densitometry data. E_{eff} is calibrated to the aluminum phantom.

DISCUSSION

The symmetry between right and left tibiae and the correlation of geometric properties from densitometry with flexural properties are striking in these sets of bones obtained from two elderly females. In spite of considerable differences in cross-sectional shape, flexural properties and degree of osteopenia among the two pairs, no statistically significant difference was found in E_{eff} , a measure of the flexural modulus of (primarily) bone mineral attenuating the beam. A trend of slightly reduced values of E_{eff} at the proximal and distal sections was noted, but the differences could not be explained by obvious factors such as an increased percentage of cancellous bone. Our initial results support the conclusion that bone mineral and its distribution are the primary determinants of flexural modulus and rigidity, respectively.

REFERENCES

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